Proving and Improving Wave Models in the Arctic Ocean and its MIZ

Prof Peter Wadhams
Cambridge Polar Consultants Ltd.
39-40 Grafton Street
Cambridge CB1 1DS, UK
Phone +44 1223 576433, Email peter.wadhams@gmail.com

Dr. Martin J Doble
Ice Ocean SASU
7 place du Château
26220 Dieulefit, France
phone: +33 (0)667 208136 email: martin@ice-ocean.com

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LONG-TERM GOALS

The long term goal of the project is to gain a significant improvement in our ability to understand, and model, the processes by which ocean waves, generated in the increasing expanses of open water which surround the shrinking Arctic ice cover, interact with the surviving ice cover and modify its properties.

OBJECTIVES

Objectives of the projects are to:

- Validate and improve the ECMWF WAM model in the Arctic, which predicts wave spectra at the ice edge on the basis of wind duration and fetch aross the open water;
- Extend the capabilities of the wavebuoys developed under the related MIZ DRI;
- Broaden the range of physical processes which contribute to modelled wave attenuation in the MIZ.

APPROACH

We make use of wave buoys based on a design developed under the MIZ DRI to carry out further specific experiments on wave reflection from ice floes and wave-induced ice breakup; we bring in the specific skills of colleagues who are skilled in wave-ice modelling (Dr Michael Meylan, U. Newcastle Australia; and Dr. Jean-Raymond Bidlot, ECMWF) to interact with the experimental program in order to improve the theory symbiotically.

WORK COMPLETED/RESULTS

Task 1.1: Validation of WAM and comparison with in-situ data.

These improvements will be tested in the Arctic as data become available from this and the closely-linked MIZ DRI.

Task 1.2: Taking WAM into the ice: Applying an enhanced WAM to delineate and track the extent and position of the wave-influenced zone.

With the latest operational model version, implemented in May 2015, WAM introduced a sea ice roughness length that depends on the sea ice concentration. The threshold (rcimin) was relaxed to allow small ice fractions, motivated by the *Andreas* et al. (2010) paper that found that the drag coefficient ovr sea ice should vary with sea ice concentration. A very recent paper by *Elvidge* et al. (2015) corroborates the earlier results and that the WAM change is in close agreement with the latest observations.

This latest version was used to run a wave hindcast for the full period of ERA-Interim. A full analysis of the data is still required. Results were compared with wave retrievals from coincident TerraSAR-X stripmaps for two swell systems travelling into the sea ice in Southeast Greenland, with a paper in preparation.

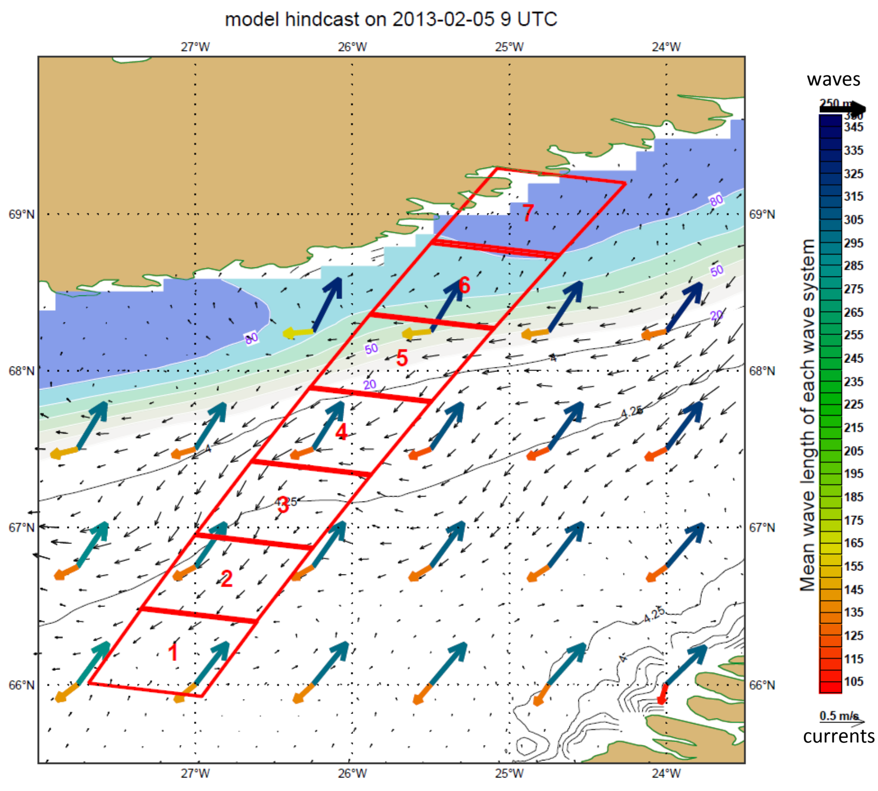

Figure 1: WAM hindcast underlaying a TerraSAR-X stripmap for swell penetrating into the East Greenland sea ice

Task 2: Development and validation of improved attenuation models and parameterisations for the MIZ.

The theoretical modeling program, led by M.H. Meylan, yielded five papers during the year, of which two are still in press. In Skene *et al*., (2015) showed that under relatively mild conditions significant quantities of water can get on to the surface of an ice floe, altering its hydrodynamics, and a model for this fluid behaviour was validated against experimental results. Meylan *et al*. (2015) validated the elastic plate model for an ice floe under relatively extreme wave conditions. Bennetts *et al*. (2015) showed that nonlinear effects can have a significant effect on wave attenuation. In Yiew *et al*. (in press) it was shown that the motion of small floes can be modelled by both potential flow theory and by a modified Morrison's equation. Toffoli *et al*. (in press) carried out a further investigation of the nonlinear effects which can dissipate wave energy. This work continues using data from wave attenuation in fields of moderate to large floes reported in earlier experimental works (e.g. Wadhams et al., 1988) in order to determine to what extent scattering theory is adequate to describe the full extent of the interaction between the waves and the ice.

Our work on wave attenuation in the advancing pancake ice zone was published in *Geophysical Research Letters* (Doble *et al*., 2015). Most importantly, we demonstrated a clear linear relation between pancake ice thickness and spectral wave attenuation for the first time, and derived a simple expression for the attenuation coefficient α in terms of the wave period and ice thickness:

$$\alpha = (pT + C).h_{\text{eq}}$$

where T is wave period in seconds, h_{eq} is the equivalent solid ice thickness, $p = -4.2\text{x}10^{-4}$ and $C = 6.2\text{x}10^{-3}$. Equivalent solid ice thickness is calculated using the measured volume fractions of pancakes (0.7) and frazil (0.4) ice (Doble *et al*., 2003).

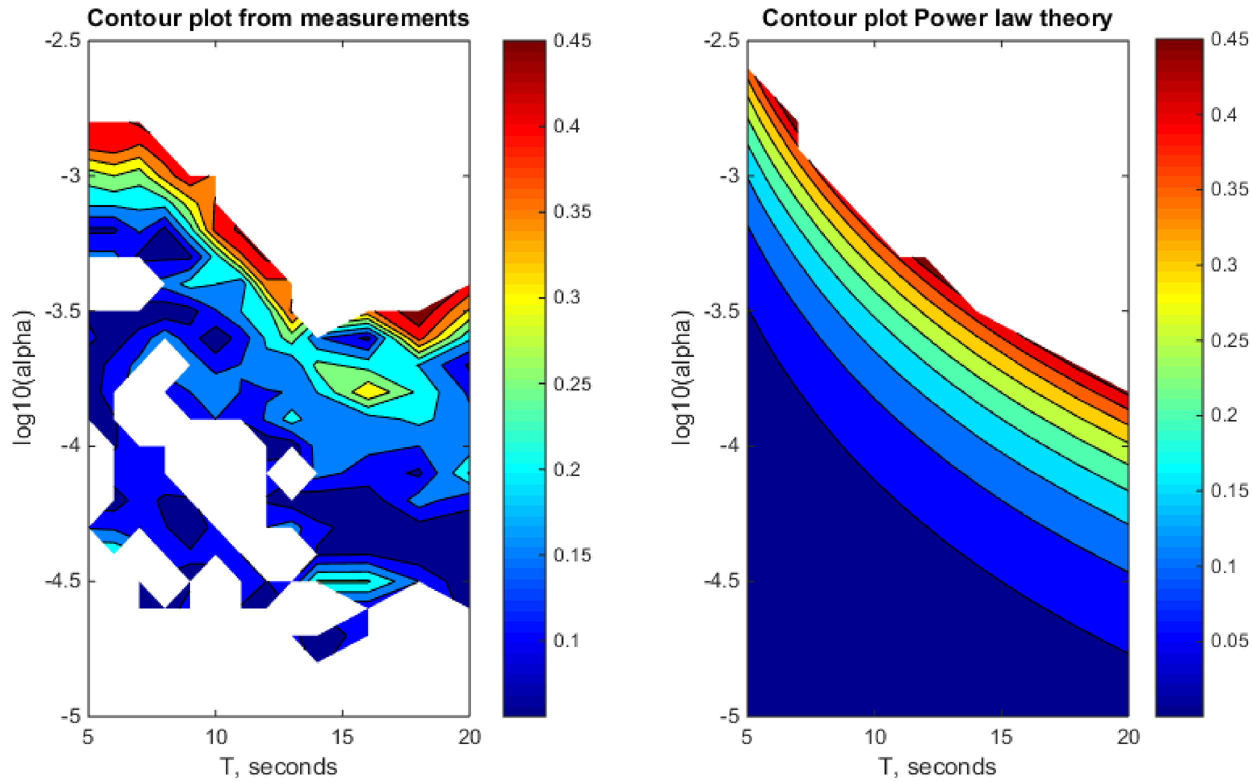

Figure 2: A contour plot showing ice thickness (colors, meters) variation with changing period (x axis) and attenuation coefficient (α). (left) The measured results: thicker ice plots to higher alphas at all periods. (right) The fitted square law equivalent.

Linking the two parameters using ice thickness output by the *Doble* (2009) pancake growth model allowed us to finally understand the highly variable field data, which hitherto has prevented its meaningful analysis. We would not expect the demonstrated linear relation to hold in the scattering regime, since the horizontal floe size (and hence the number of floes edges in a given path length) is the dominant factor there (a squared relation), despite the scattering term also having a linear ice thickness relation, as already known (Wadhams, 1975).

A linear relation between modeled (log) eddy viscosity and pancake/frazil ice thickness was also newly demonstrated using these data, with fitted eddy viscosities at the ice water boundary ranging from $0.01 m^2 s^{-1}$ (ice thickness = 10 cm) to $0.2 m^2 s^{-1}$ (ice thickness = 50 cm). These values are encouraging: available field measurements of eddy viscosity under large-ice floes report the value of $0.24 \times 10^{-2} m^2 s^{-1}$ in the central Arctic Ocean (Hunkins, 1966); in the Antarctic MIZ, Weddell Sea, slightly larger values were reported ranging from 1.6×10^{-2} $m^2 s^{-1}$ (Brennecke, 1921) to 2.0×10^{-2} $m^2 s^{-1}$ (McPhee and Martinson, 1994). Since the variability of eddy viscosity reflects the actual turbulence level at the measurement site, the higher values found in the present study are expected, since the turbulence levels during our measurements (*e.g.*, H_s = 3.7 m) are considerably higher than for the quoted cases. Turbulence levels are nevertheless low enough that the assumed laminar motion of the model is not violated. The linear approach we have adopted thus appears valid. Clearly, there will be nonlinear effects, but for the amplitudes and periods present in these field data, the linear effects are dominant.In this context, it might be expected that eddy viscosity would negatively correlate with ice thickness, since the wave height between buoys drops through the record. We suggest that the increased

underside roughness of the rafted pancakes as they compact (*c.f.* the rather smooth underside of individual pancakes) dominates the evolution of eddy viscosity in this time series.

The aim of the study was to provide computationally-simple parameterizations for wave attenuation in pancake/frazil ice. Equations in ice thickness and wave period can now be used in research and operational models to determine the extent of the wave-influenced pancake zone, though further measurements to verify the wider applicability of this data set are required. Systematic SAR observations from available satellite platforms can provide such measurements. Combining the new expression for α as a function of the wave period and ice thickness with the predictions of the two-layer viscous model, an inversion procedure of the SAR image spectra can be envisaged to estimate the ice thickness over fields of pancakes in the MIZ at unprecedented spatial resolution.

Such vast fields of pancake ice have traditionally only been associated with the advancing Antarctic MIZ, and, on a smaller scale, the Greenland Sea Odden which is important for deep convection. The increased open water area present in the autumn Arctic Ocean, particularly in the Beaufort Sea (Lee *et al*., 2012; Jeffries *et al*., 2013), will make it increasingly applicable to those seas as well, and these findings are thus particularly timely.

Task 3: An ice edge reflection and scattering experiment

A set of eight wave buoys was constructed for the planned *R/V Sikuliaq* research cruise (30 September - 10 November 2015). The heart of the wavebuoys developed under the MIZ DRI was upgraded with a new attitude and heading reference system (AHRS), replacing the obsolescent SBG IG-500A devices with significantly-improved SBG Ellipse-A units. The buoys also added a high-accuracy, phase-resolving GPS compass (Hemisphere H-102), allowing calculation of a reliable heading for the directional spectra, whatever the magnetic environment and proximity to the magnetic pole, as well as giving centimetric-accuracy GPS positions at 10Hz. The buoys were completed and shipped to Seattle in time to be included in the APL/UW container/barge shipment to Nome, with custom floats and lithium battery packs arriving direct from the US manufacturers.

We implemented code for the calculation of directional spectra, using a new wavelet method, following the recent appearance (Donelan *et al*., 2015) of favourable comparisons between this and existing directional methods (*e.g*. maximum entropy method). The various techniques will be applied to *Sikuliaq* data, giving further insight into their directional characteristics, in conjunction with "ground truthing" from the installed WaMoS radar and LIDAR overflights by the NRL aircraft.

A specific set of experiments is planned in which the array is deployed partly on floes near the ice edge and partly in open water just seaward of the ice edge. The aim is to maintain and measure the distances from the ice edge of the two sets of buoys, in order to measure (a) the reflection coefficient from the front of the icefield, a measure of the nature of the scattering process, (b) the directional spectrum inside the ice at different distances, giving attenuation rates and the change in spread of the spectrum with distance, a quantity of considerable importance to the understanding of the scattering process and only measured on one previous occasion (Wadhams *et al*., 1986). In addition, the buoys will be contributed to all other experiments on board in which they may be useful, particularly longer-scale waves-in-pancake ice experiments during the October phase of ice edge advance and as precise GPS reference points for under-ice AUV surveys.

An aspect of the wave-ice interaction process is the break-up of floes by wave-induced flexure, which controls the final floe size distribution achieved in an MIZ dominated by large waves. Data on the break-up of a large tabular iceberg by swell, measured in Baffin Bay, were published (Wagner et al., 2014; Stern et al., 2015), which provides a test of mechanical models of the strain field in elastic sheets, and it is hoped that further direct measurements of floe flexure will improve this understanding further.

Travel

- Wadhams and Doble attended the mid-term review in Washington D.C. on 26-31 October 2014
- Wadhams and Doble attended the DRI meeting at APL/UW Seattle on 21-22 May 2015.
- Wadhams, Doble and Research Assistant Robin Clancy travelled to Nome on 28 September 2015, to join the *R/V Sikuliaq* research cruise.

IMPACT

The application will be to the full understanding of the role of waves in determining the shape and development of the ice edge region during the summer and autumn advance period. The presence or absence of waves determines the type of ice that is first generated at the advancing ice edge (frazil and pancakes or nilas) and profoundly influences the rate at which this first, young, ice is grown, as well as its compaction, drift and the production of fractured floes/brash at the edge. The resulting ice type then affects the attenuation of the waves as they travel through the ice edge region, determining the width of the wave-influenced zone in a constantly evolving feedback relation. Our modelling of wave-ice interaction processes, and especially our controlled experimental observations of waves in ice, will help solve this set of physical problems.

RELATED PROJECTS

"Wave-ice interactions and the Marginal Ice Zone", MIZ DRI, Award Number N0014-12-1-0130

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